70/80 GHz Recon Petition (WT 02-146): Computer Simulation of mmWave Interference

August 24, 2004

Cisco Systems

Outline

- Overview of recon petition
- Market considerations
- Simulation and analysis results
- Conclusions

Overview of WCA Recon Petition

- The Commission should require advance coordination with non-Government users.
- The Commission should leave the 70/80 GHz bands unchannelized and should eliminate or reduce the channel loading requirement.
- The Commission should embrace industry proposals for:
  - A power/gain tradeoff
  - ATPC for links with EIRP >23dBW
  - A power spectral density limit
- The Commission should adopt WCA's proposed interference protection criteria.
- The Commission should authorize conditional operation for blanket license applicants.

Overview of Market Drivers

Market Considerations	Technical Solutions
Enterprise and service provider deployments enabled	E-licensing
Fiber-equivalent service	Upfront interference protection (path coordination) C/I protection limit and PSD limit to preserve fiber-equivalent service from early deployment of low-rate digital services and analog service (e.g. video distribution) on same rooftop
Improve equipment aesthetics on building (small antennas) Deployment ease (antenna alignment, tolerance to tower sway)	Lower antenna gain leading to power/gain trade-off in order to maintain high deployment density (links/km^2)

Overview of Market Drivers (cont.)

Market Considerations	Technical Solutions
Deployment from fiber points-of-presence (Hub and Spoke)	Automatic transmit power control (ATPC) for high link density on same rooftop Harmonized frequency plan
Technical rules which facilitate lower cost equipment without sacrificing link density	Small antenna size No bps/Hz limit Reduced ATPC range for low power devices Reasonable antenna RPE mask

Deployment Topologies

- "Random" deployments
  - Steady accumulation of independent links wherever needed by individual enterprises for campus deployments
  - Aerial view of these links would appear as though the locations were randomly assigned
- "Hub and Spoke" deployments
  - There are about 8000 fiber POPs today
  - Business proximity[1]
    - ✓ 750k business buildings in US with >20 employees
    - ✓ Only ~5% of these buildings have fiber connections today
    - ✓ ~75% of these buildings are within 1 mile of a Fiber Hotel
  - These facts underscore the importance of the "Hub and Spoke" deployment

[1]Source: RHK

Hub and Spoke Deployment Considerations

- Single Service Provider deployment
  - SP acquires roof rights for all 70/80 GHz links on fiber POP
  - SP responsible for link performance and availability
  - SP likely deploys radios from a single vendor
  - SP has sophisticated radio planning and deployment departments; can readily resolve installation and commissioning difficulties
- Enterprise deployment
  - E-licensing removes barrier to entry of licensed spectrum availability
  - Enterprise customer owns and installs link from spoke to hub
  - Installation and commissioning costs must be kept low
  - Customer not typically equipped to resolve co-location interference problems
  - Hub location has many radios, independently managed, from multiple vendors (multi-SP deployments share this characteristic)
- Technical rules must support/promote both deployment models—market will decide preferred model(s)

Computer Simulation Results

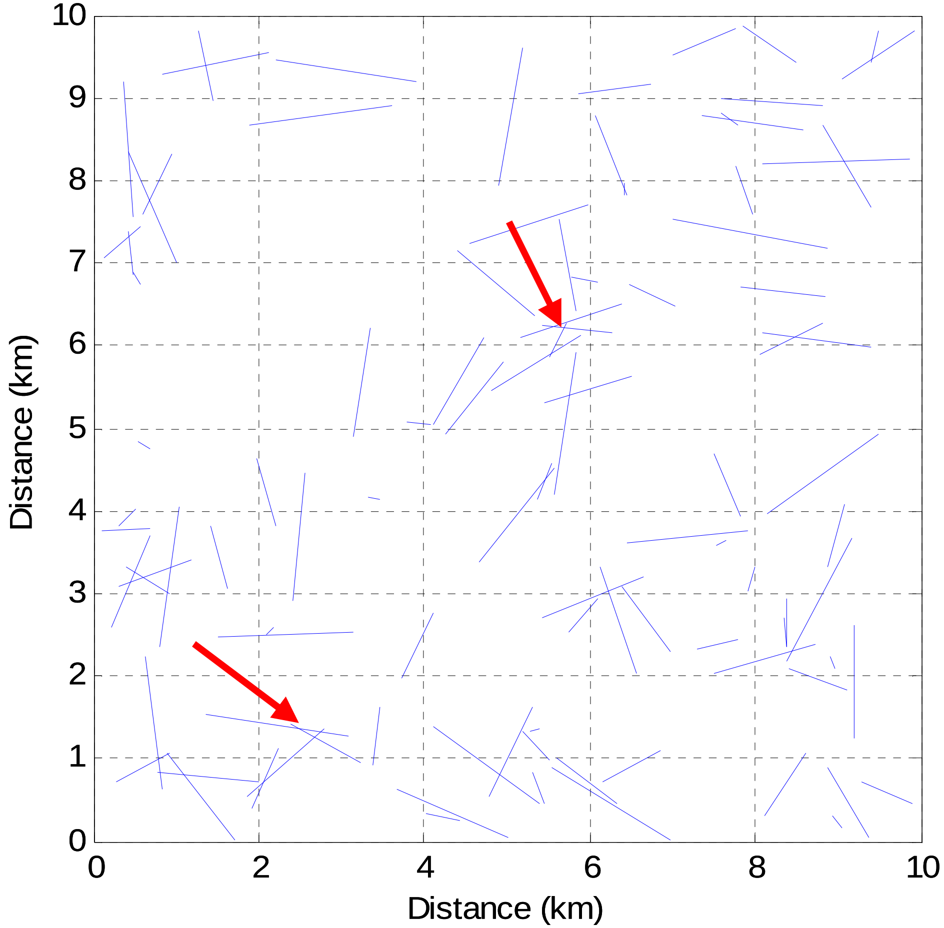
Simulated Path Coordination Study Objectives

- The objective of this study is to develop spectrum and deployment rules which maintain high deployment link density in both random and hub-and-spoke scenarios.
- The simulation platform is used as a tool to examine the levels of interference encountered for deployed P2P links in the 70/80 GHz bands.
- The levels of interference are examined for different rain environments, deployment densities, and antenna beamwidths.
- Simulations employ dual-band FDD radios and cross-polarized links.
- All simulation results presented herein assume completely co-channel and overlapping signals.
- Results from this study were presented as an invited paper at TSMMW2004 (March 2004 in Japan) at the request of Mike Marcus.

Random Deployment Simulation Methodology

- Monte Carlo simulation of a collection of links randomly distributed in a 10 km by 10 km area (roughly the size of San Francisco).
- The initial location of one side of each link is in a randomly placed position and height above level ground (ranging from 5 to 50m).
- The direction of each link is also uniformly random distributed in azimuth.
- The range of each link is uniformly random distributed between 100 meters and the maximum range per the link budget of the specific simulation scenario.
- All simulated transmitters in the 70-GHz band are assumed to have identical center frequency and bandwidth; likewise for the 80-GHz band.
- The number of links in the simulation is a function of the simulated link density.
- The red arrows highlight potential points of interference where the end of one link is near the middle of the path for another link.

Example of 1 link/km^2 deployment density



Simulation Methodology

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- In both scenarios, the received signal level is calculated from every other terminal in the system.
  - The calculations take into effect the angle off boresight at the transmitter and receiver, the free-space propagation loss, atmospheric absorption, and rain attenuation at 99.99% availability.
- Required C/(I+N) is 14 dB.
  - The level of 14dB is based on BPSK modulation at BER levels appropriate for fiber-equivalent service.
- The transmitter signal level is set such that the achieved C/N is a minimum of 1 dB above the required level for the longest links in the rain.
- In shorter links, the transmitter power level is set according to the ATPC rules described later in the presentation.
- If the received C/(I+N) of a link is below the required level, the link fails.

Calculation of Availability

- 100 random deployments were simulated, and the average number of failed links per deployment was calculated.
- For random deployment, 100 random deployments were performed for link densities varying between 0.1 and 10.0 links/km^2.
- For hub-and-spoke deployment, 100 random deployments were performed for number of links on a roof top increasing from 2 to 35.

Example Link Budgets for Range Calculations

44-dBi Gain Antenna

1-foot dish

Parameter		
Carrier Freq (GHz)	71	71
Transmit Power (dBm)	**15**	**15**
Tx Antenna diameter (in)	**12**	**12**
Anenna efficiency (%)	50.0	50.0
Antenna boresight gain (dBi)	44.0	44.0
EIRP (dBm)	59.0	59.0
Bandwidth (MHz)	1000	1000
NF (dB)	8	8
Noise Power (dBm)	-76.0	-76.0
Rain Region	K	K
Rain Availability	0.9999	0.99999
Rain Attenuation (dB/km)	16	31
Oxygen Attenuation (dB/km)	0.4	0.4
Path length (km)	**1.8**	**1.1**
Path length (miles)	**1.1**	**0.7**
Received Antenna gain (dBi)	44.0	44.0
Received Power (dBm)	-61.0	-61.0
Received C/N	15.0	15.0
Required SINR (dB)	13	13
Implementation loss (dB)	1	1
Interference Margin (dB)	1	1
Link Margin	0.0	0.0

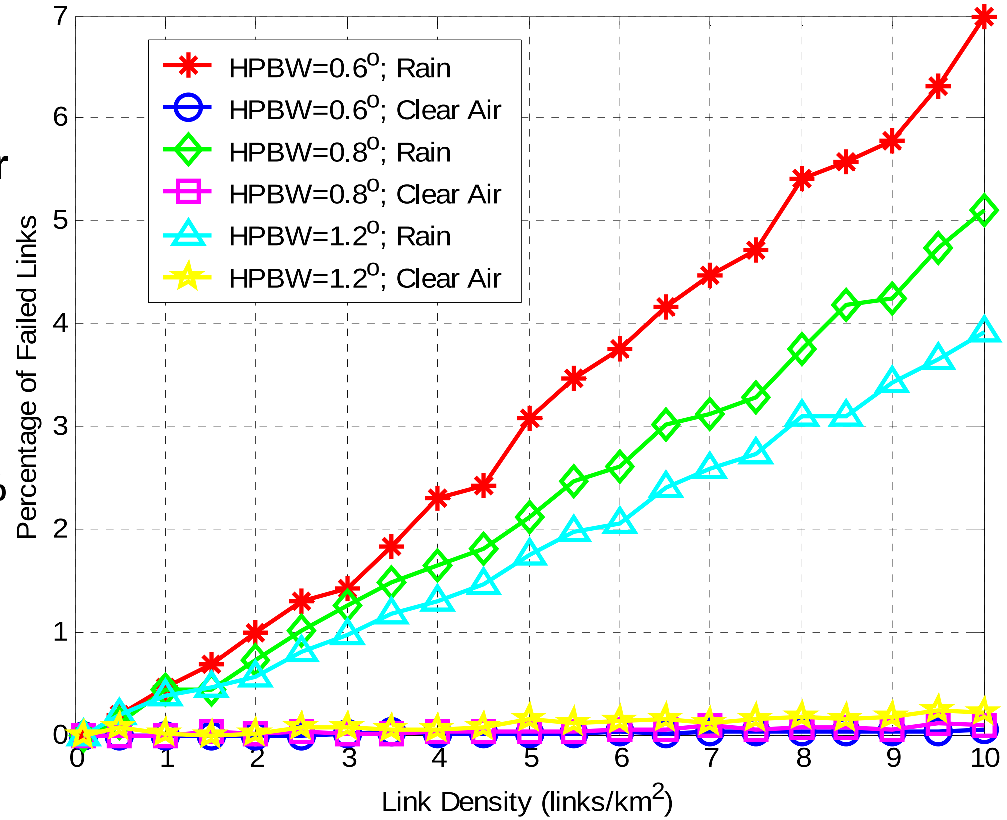
50-dBi Gain Antenna

2-foot dish

Parameter		
Carrier Freq (GHz)	71	71
Transmit Power (dBm)	**35**	**35**
Tx Antenna diameter (in)	**24**	**24**
Anenna efficiency (%)	50.0	50.0
Antenna boresight gain (dBi)	50.0	50.0
EIRP (dBm)	85.0	85.0
Bandwidth (MHz)	1000	1000
NF (dB)	8	8
Noise Power (dBm)	-76.0	-76.0
Rain Region	K	K
Rain Availability	0.9999	0.99999
Rain Attenuation (dB/km)	16	31
Oxygen Attenuation (dB/km)	0.4	0.4
Path length (km)	**3.4**	**1.9**
Path length (miles)	**2.1**	**1.2**
Received Antenna gain (dBi)	50.0	50.0
Received Power (dBm)	-61.0	-61.0
Received C/N	15.0	15.0
Required SINR (dB)	13	13
Implementation loss (dB)	1	1
Interference Margin (dB)	1	1
Link Margin	0.0	0.0

Performance as a Function of Antenna Half Power Beamwidth

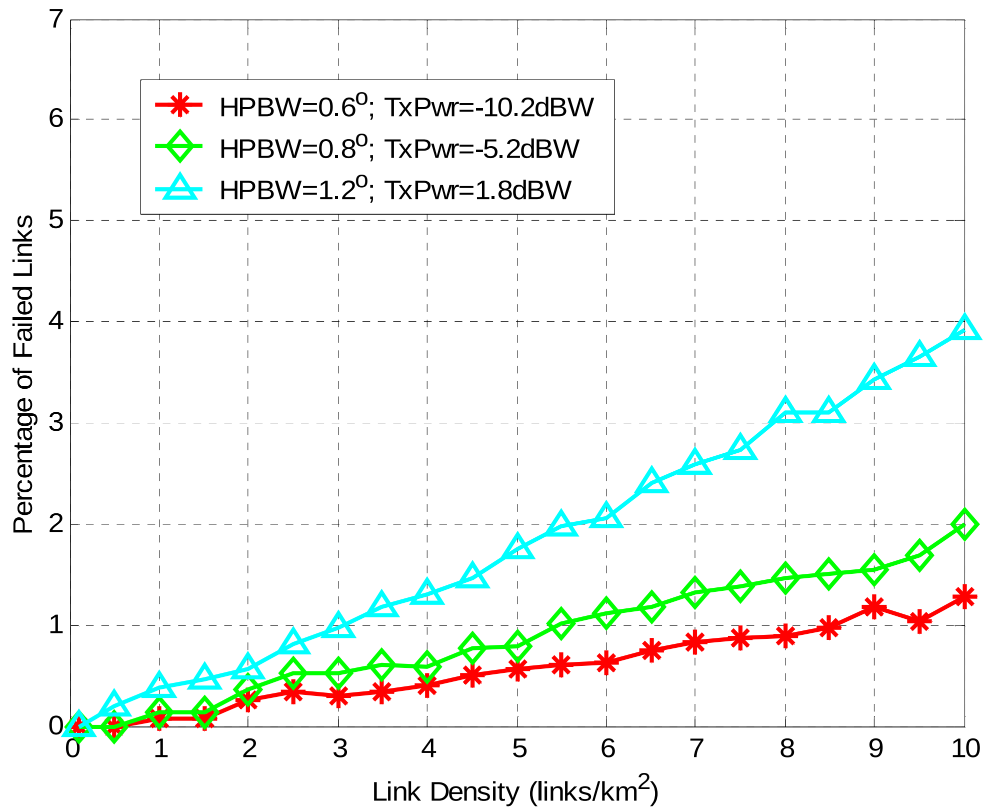
- **Random deployment simulation results comparing link density performance with different half power beamwidth.**
- **The percentage of link failures in clear air is negligible.**
  - **In clear air, links have large fade margins resulting in minimal impact from interference.**
- **In the rain, the links are faded and more sensitive to interference.**
  - **The percentage of link failures is below 7% at 10 links/km^2, and decreases as the HPBW increases from 0.6º to 1.2º.**
- **The implications of these results are that lower gain antennas will not cause a measurable increase in interference.**
  - **Lower antenna gains necessitate shorter path lengths.**
  - **With shorter path lengths, there is more separation between links for a given link density.**
  - **This reasoning holds for links engineered for 99.999% path availability— for a given antenna gain, links with be shorter than those engineered for 99.99% availability.**



- **These simulation results employ a transmitter power of 1.5 Watts for each case.**
- **Maximum path length of 2.7 km**

Performance as a Function of Antenna Half Power Beamwidth with Equal Path Length

- **In these simulation results, the maximum path lengths are made equal for all three antenna HPBW's by reducing the maximum transmitter power.**
  - **Maximum path length of 2.4km**
- **Now the percentage of link failures decreases as the HPBW decreases.**
- **With equal maximum path length, devices with narrower beam, higher gain antennas require less transmit power, resulting in lower interference levels in the system.**

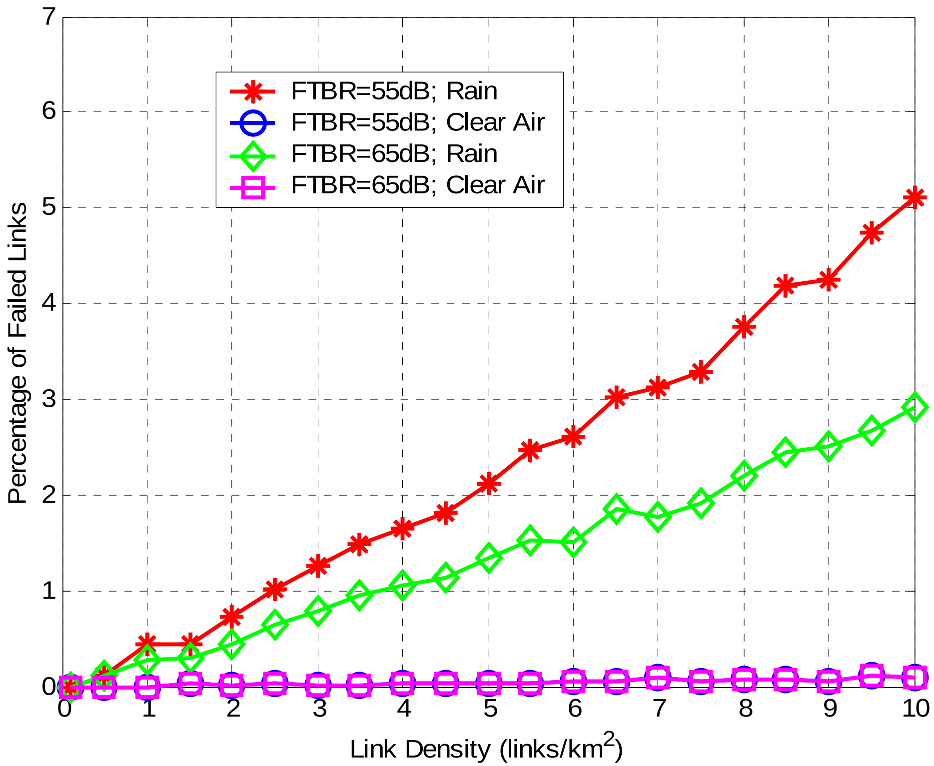


Industry Proposal for Power/Gain Tradeoff

- Based on these results, a 2dB reduction in maximum allowable EIRP for every 1dB reduction in antenna gain is proposed for antennas with gain less than 50 dBi.
- The maximum allowable EIRP (in dBW) for antennas with gain less than 50 dBi becomes 55 - 2 $\times$ (50 - G).
- Example:
  - Equipment manufacturer selects a 46-dBi gain antenna
  - Maximum permitted EIRP = 47dBW (enforced as part of the equipment certification process)
  - ATPC, if provided, reduces power further under clear-air conditions (more detail later in presentation)

Antenna Front-to-Back Ratio

- **The results on the right illustrate simulations with an antenna front-to-back ratio having 10dB higher attenuation between 100º to 180º than given our minimum radiation suppression table.**
- **Higher attenuation results in improved system performance, but not enough in our view to warrant the significant increase in cost to achieve 65-dB radiation suppression.**



- **Simulation system parameters:**
  - **0.8º HPBW**
  - **Transmitter power of 1.5 Watts**

Industry Proposal for Antenna RPE

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- **Based on these simulations and vetting proposed specifications with millimeter-wave antenna manufacturers, the industry proposed a antenna radiation pattern envelope (RPE).**
- **This led to industry consensus on the follow antenna rules:**

Frequency (MHz)	Cat	Max BW to 3 dB points (Included angle in degrees)	Min gain (dBi)	5° to 10°*	10° to 15°*	15° to 20°*	20° to 30°*	30° to 100°*	100° to 140°*	140° to 180°*
				Minimum radiation suppression to angle in degrees from centerline of main beam in decibels						
71,000 to	**A**	**1.20**	**43‡*L_1**	**35**	**40**	**45**	**50**	**50**	**55**	**55**
76,000	**B**	**1.20**	**43‡**	**35**	**40**	**45**	**50**	**50**	**55**	**55**
81,000 to	**A**	**1.20**	**43‡*L_1**	**35**	**40**	**45**	**50**	**50**	**55**	**55**
86,000	**B**	**1.20**	**43‡**	**35**	**40**	**45**	**50**	**50**	**55**	**55**

‡ Antenna gain less than 50 dBi (but greater than 43 dBi) is permitted with a proportional reduction in maximum authorized EIRP in a ratio of 2 dB of power per 1 dB of gain, so that the maximum allowable EIRP (in dBW) for antennas of less than 50 dBi gain becomes +55 – 2 (50 – G), where G is the antenna gain in dBi.
*** For the bands 71-76 GHz and 81-86 GHz, the following specification is included for minimum radiation suppression L1 at angles from 1.2º to 5º from centerline of main beam in dB: L1 = G – 28 .**

Industry Proposal for Antenna RPE (cont.)

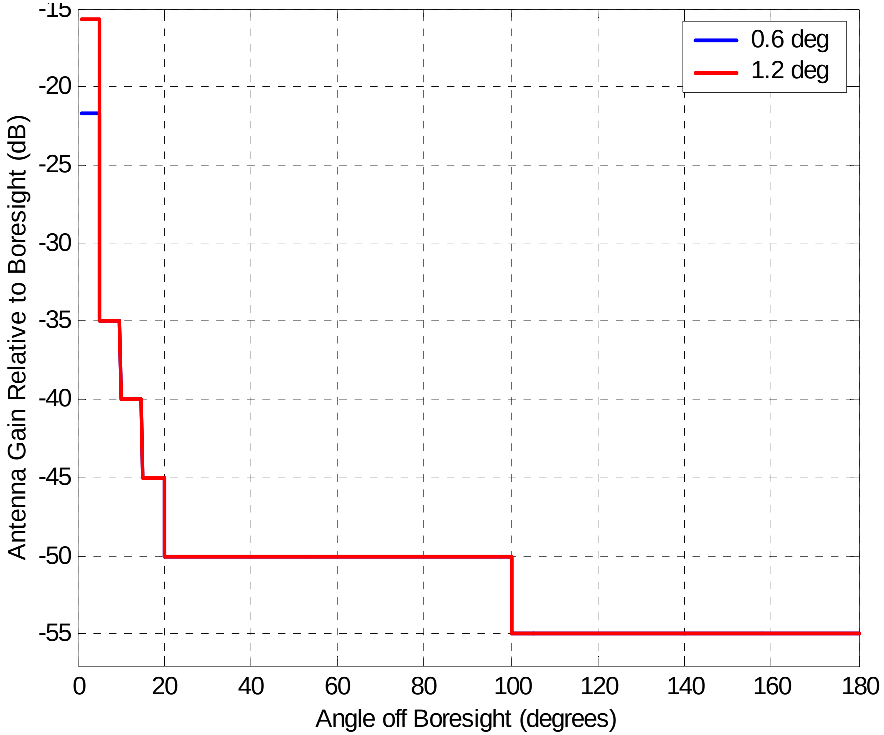
- **Industry consensus cross-polarized RPE:**

Minimum cross-pol radiation suppression to angle in degrees from centerline of main beam in decibels

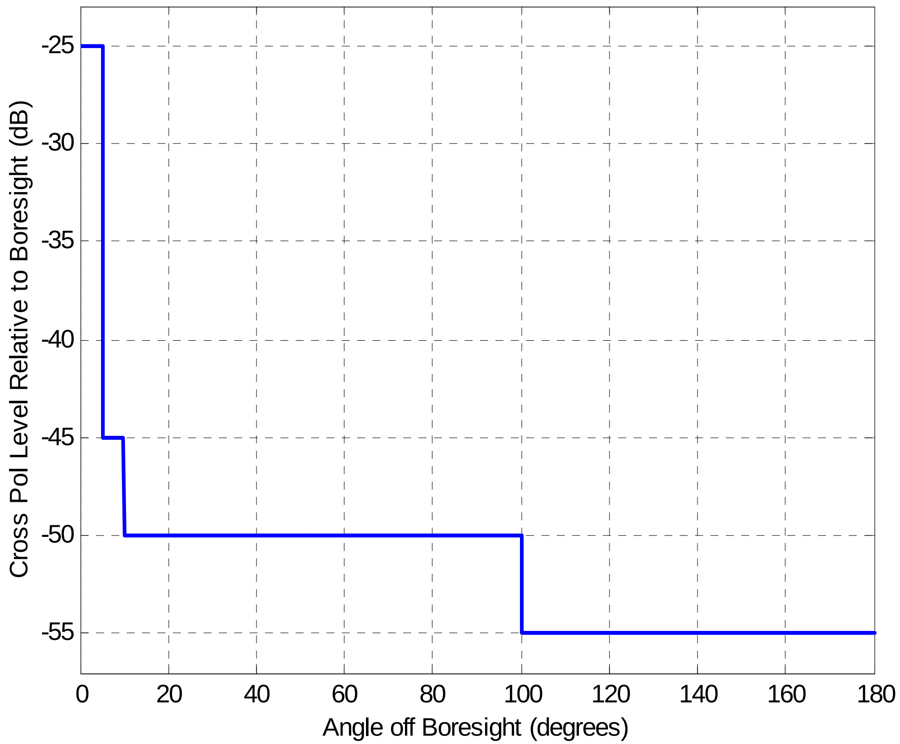
Frequency (MHz)	Category	0° to 1.2°	1.2° to 5°	5° to 10°*	10° to 15°*	15° to 20°*	20° to 30°*	30° to 100°*	100° to 140°*	140° to 180°*
71,000 to	**A**	**25**	**25**	**45**	**50**	**50**	**55**	**55**	**55**	**55**
76,000	**B**	**25**	**25**	**45**	**50**	**50**	**55**	**55**	**55**	**55**
81,000 to	**A**	**25**	**25**	**45**	**50**	**50**	**55**	**55**	**55**	**55**
86,000	**B**	**25**	**25**	**45**	**50**	**50**	**55**	**55**	**55**	**55**

Graphical Portrayal of Antenna Mask

Co-Polarized Mask



Cross-Polarized Mask

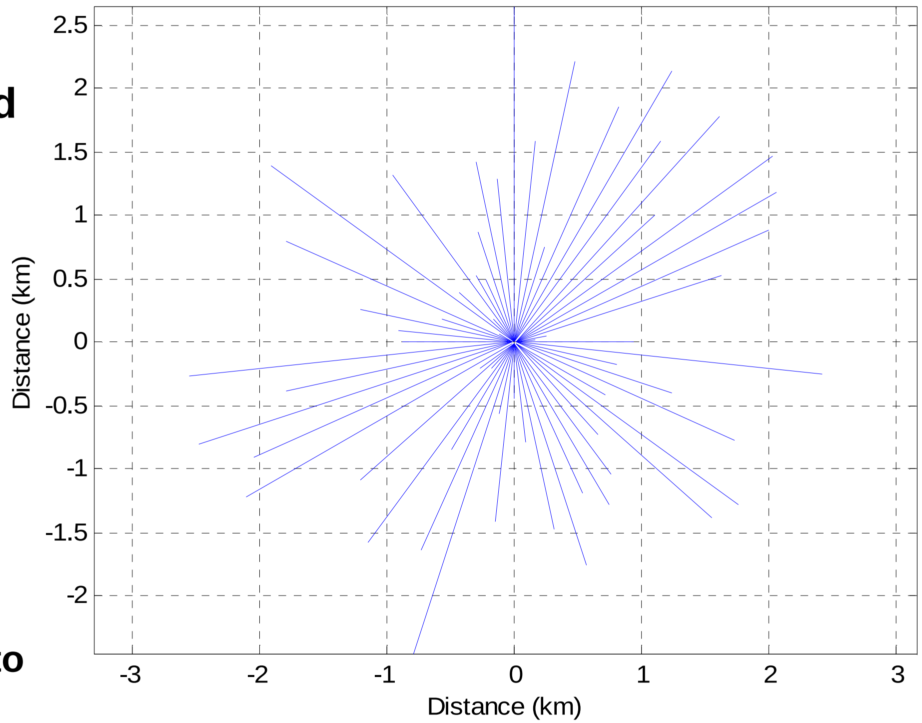


- **On co-polarized mask, for angles between 1.2° - 5 ° off boresight, minimum radiation suppression (dB) = boresight gain – 28**
- **Note: these antenna masks were used for all computer simulations described in this presentation**

Hub-and-Spoke Deployment Simulation Methodology

- **Links are evenly spaced in azimuth, with the angle separation a function of the number of links.**
- **The terminals at the hub are evenly spaced on a circle of radius 10 m.**
- **The hub height is fixed at 50 m.**
- **All out-bound transmissions are assigned to one frequency band, and all in-bound transmissions are assigned the other frequency band.**
  - **This criterion eliminates, or at least minimizes, so-called "bucking scenarios" where transmitters on a rooftop are operating on the same or overlapping frequencies as nearby receivers.**
  - **Such a scenario would be inherently difficult to coordinate.**
  - **This constraint also maximizes the probability a licensee may "upgrade" their link rate when business needs dictate because in many cases it will be possible to coordinate the entire 5 GHz in each direction**
- **Adjacent links are assigned opposite polarizations.**

Example with 6º angular separation

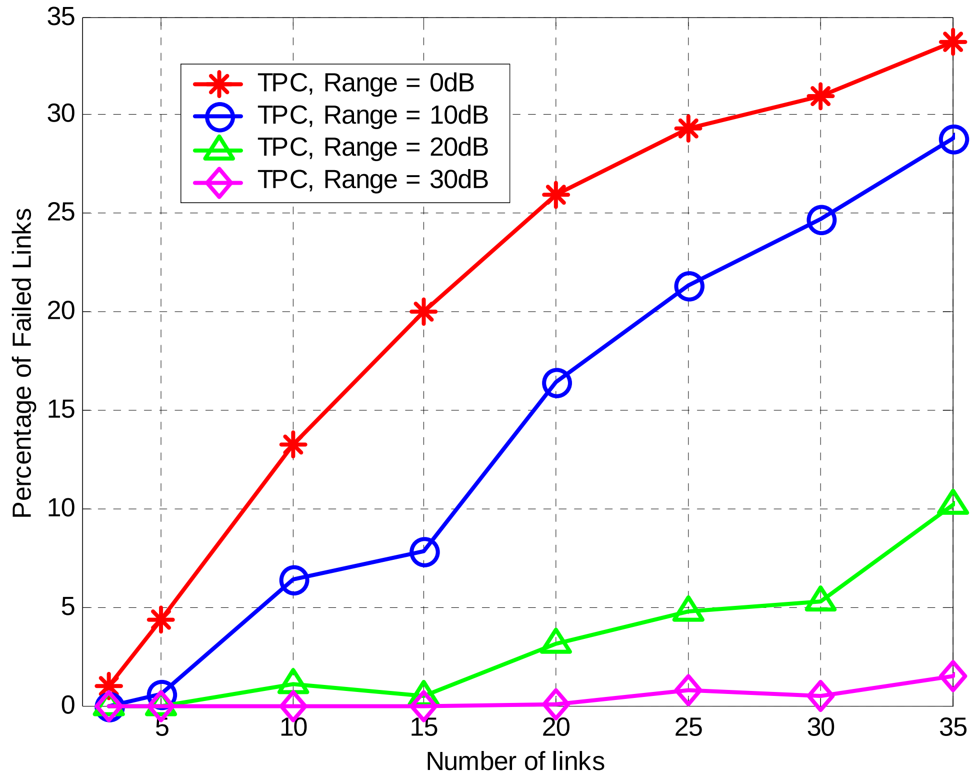


Automatic Transmitter Power Control (ATPC)

- In the 70/80GHz band, devices may require up to 50 dB of link margin to contend with rain fades.
- If all devices transmit at their maximum power levels, the interference in the environment will be unnecessarily high and link densities will be lower.
- This situation is especially true in a hub-and-spoke environment where devices at the hub will be spaced close to each other.
  - In this scenario severe “near/far” problems can occur when a short-range link is on an adjacent “spoke” to a long-range link.
  - During rain, the long-range link’s receive signal will be faded to its minimum level.
  - However, the short range link will not be significantly attenuated by rain.
  - When ATPC is employed, the short-range link reduces its output power thereby improving the C/I of the longer link.
- The simulated algorithm sets the transmitter power such that the received C/N is within 10dB of the target subject to the transmit power dynamic range.
  - The 10dB margin gives some time for the algorithm to react to a change in rainfall rate as well as design choices in ATPC implementation.

Transmitter Power Dynamic Range

- **These results illustrate the hub-and-spoke system performance in the rain as a function of transmitter power dynamic range.**
- **The percentage of failed links drops from 34 to almost zero as the dynamic range increase from 0dB (no ATPC) to 30dB.**
- **To expect that all products be built with 30dB transmitter power dynamic range would result in higher product costs.**
- **It would be desirable that low power, low cost devices only require a small transmitter power dynamic range, and higher power, higher cost devices require higher transmitter power dynamic range.**



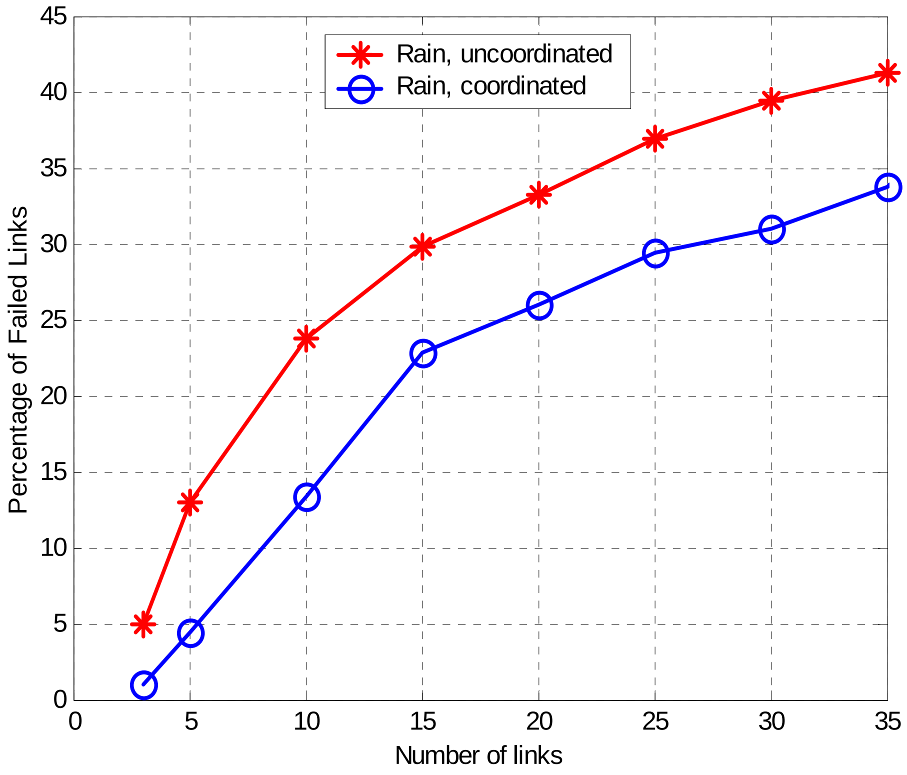
- **Simulation system parameters:**
  - **0.8º HPBW**
  - **Transmitter power of 1.5 Watts**
  - **Maximum path length of 2.7 km**

Industry Proposal for Dynamic Range for ATPC

- **We propose the following automatic transmitter power control range (ATPC) range to be as follows:**
  - **Minimum ATPC dynamic range = maximum(0, EIRPdBW – 23)**
  - **The ATPC function shall set the C/N at the receiver to <T+10 dB, where T is the static threshold of the receiver, or**
  - **Reduce the transmitter's output power to the specified minimum (e.g., this situation occurs over a short link range in clear air).**
- **Example:**
  - **Low Power device: Tx power = 15dBm; 44dBi antenna**
    - ✓ **EIRP = 29dBW**
    - ✓ **Required dynamic range = 6dB**
  - **High Power device: Tx power = 30dBm; 50dBi antenna**
    - ✓ **EIRP = 50dBW**
    - ✓ **Required dynamic range = 27dB**

Path Coordination

- **In the hub-and-spoke simulations:**
  - **All out-bound transmissions are assigned to one frequency band, and all in-bound transmissions are assigned the other frequency band.**
  - **Adjacent links are assigned opposite polarizations.**
- **In the random scenario, frequency directions and polarizations are modified on failed paths in an attempt to improve the link performance.**
- **All simulated transmitters in the 70-GHz band are assumed to have identical center frequency and bandwidth; likewise for the 80-GHz band.**



- **These simple enhancements improve link density, illustrating the benefit of path coordination.**

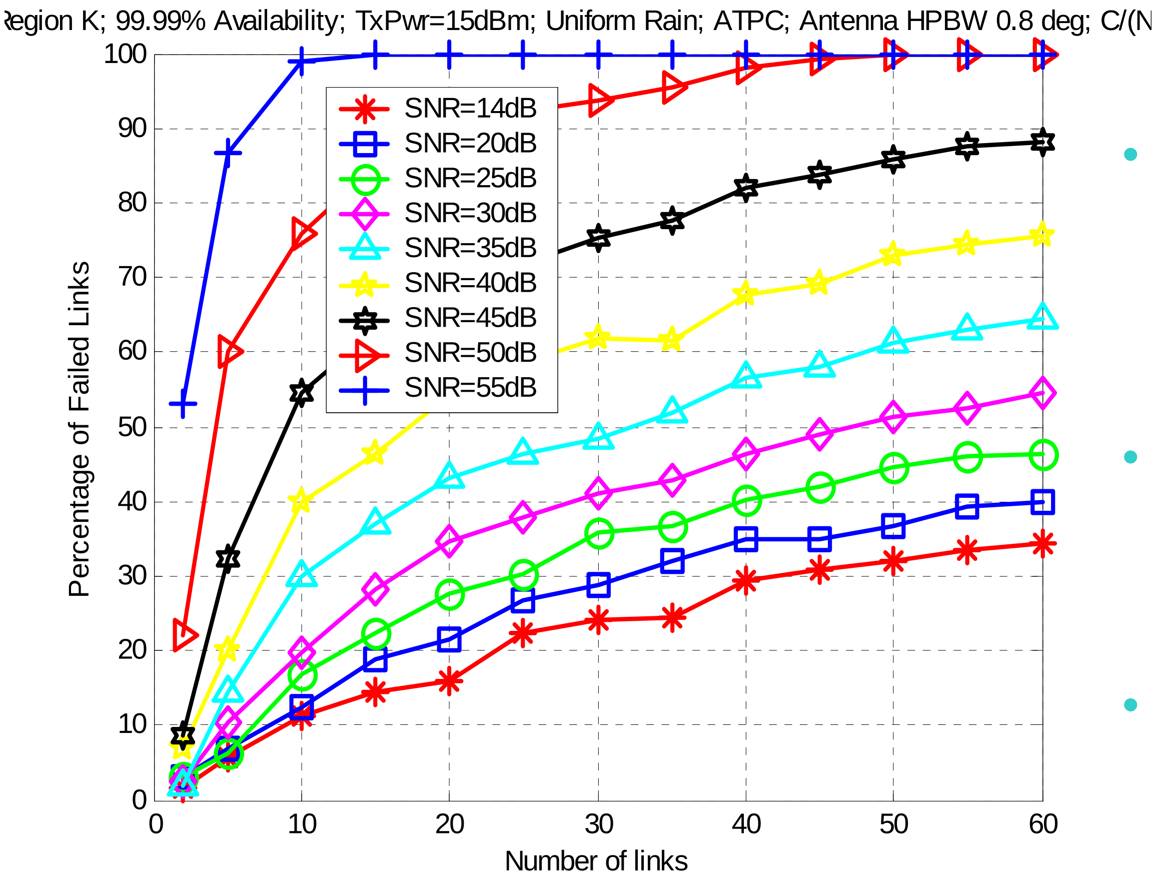
Power Spectral Density Limits

- The 70/80GHz bands should be preserved for high bandwidth radios as a wireless alternative for fiber-rate services. Spectrum exists at lower frequencies for narrow band services.
- Currently there are no regulations restricting a device from transmitting an EIRP of 55dBW in an arbitrary small bandwidth (*e.g.,* 1MHz).
- Such devices would have significantly different spectral and spatial properties.
  - Interference between narrow band and wide band devices would be difficult to predict with respect to measurement and calculation of C/I.
  - Narrow band devices will have much longer ranges, and would have wide exclusion zones, significantly reducing the deployment of wide band devices.
  - Predicted link densities from simulations have assumed similar wideband devices. Results will not apply to interference from narrowband devices.
- Allow for narrowband devices, but restrict the power spectral density.
- Industry proposal
  - Transmissions in the 71-76 and 81-86 GHz bands shall be subject to a maximum power spectral density limit of 150 mW per 100 MHz.

Industry Proposal for Interference Protection Criteria

- **Proposed rule**
  - ➢ **In these bands the interference analysis shall be conducted on a full-band basis (71-76 or 81-86 GHz). Thus for comparison to the following criteria, the carrier-to-interference ratio (C/I) shall be calculated as the ratio of the total carrier power to the total interference power in the 71-76 GHz or 81-86 GHz band. C/I objectives in excess of 36 dB shall not be protected in these bands.**
- **Unduly high C/I objectives will limit deployable link density.**
- **While analog modulation may require 55dB C/I or greater, the difference between 55 and 36 reflects the expectation of filtering on the analog receiver relative to wideband digital modulation.**

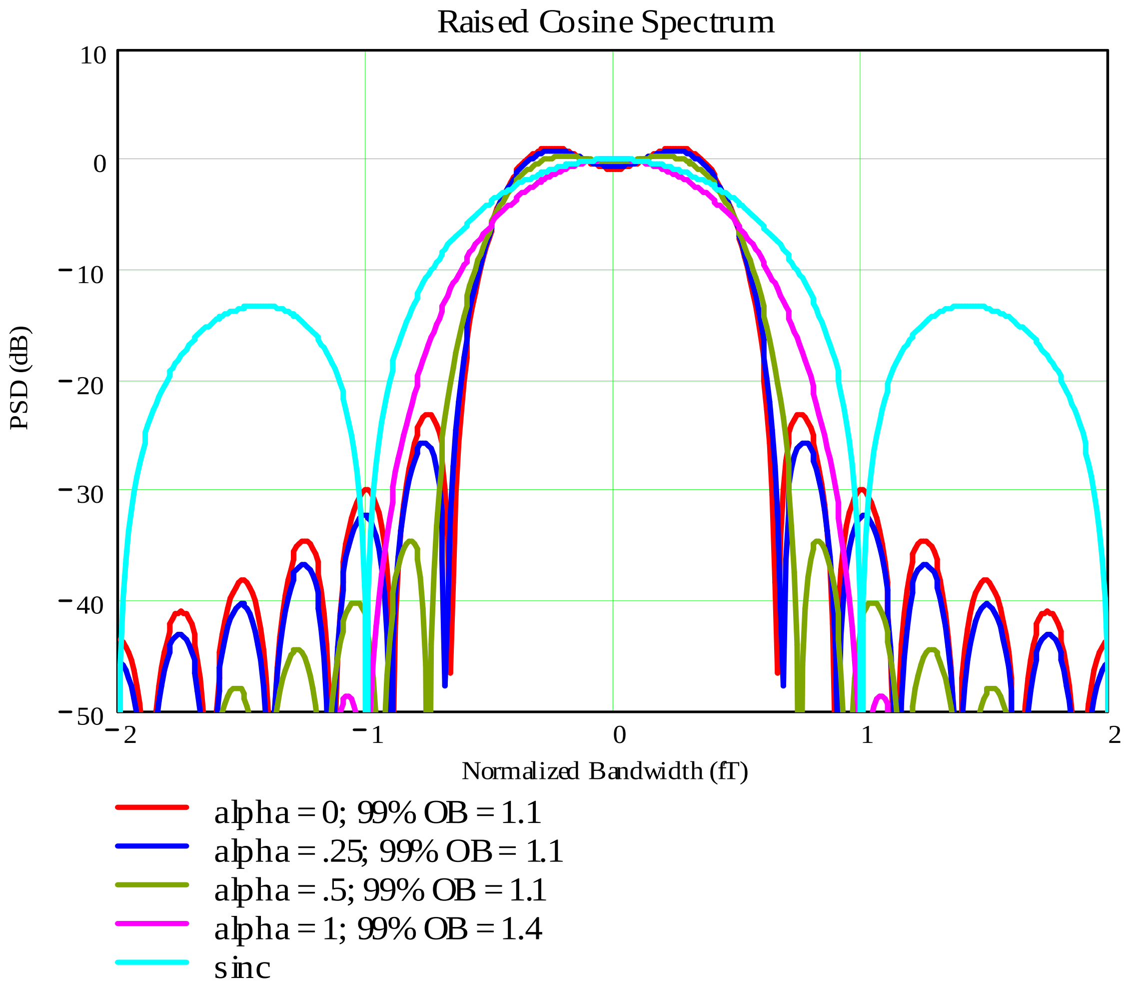
Basis for Maximum Required C/I



- **As the required C/I is increased, the number of links at a given percentage of failed links decreases.**
- **In a hub-and-spoke deployment, links requiring 55dB C/I result in percentage of failed links even with only two links.**
- **Devices requiring unduly high required C/I will exclude other links from being deployed.**
- **A maximum protected C/I of 36dB represents a reasonable compromise between link deployment density and allowing a range of device types.**

Spectral Efficiency

- The figure illustrates the spectral occupancy with raised cosine pulse shaping
- For low barrier to entry, it is desirable to implement simple modulation schemes
- The requirement of a minimum spectral efficiency of 1 bps/Hz *prohibits* the use of binary signaling such as OOK and BPSK
  - bps/Hz = (bit/symbol)*(symbol/sec)/Hz= (bit/symbol)/(BW*T)
  - Uncoded BPSK: (1bit/symbol)/(1.4 BW*T)=0.7bps/Hz
  - The bandwidth was selected based on the pink line (alpha=1) and measuring the 99% occupied bandwidth
- If channel coding is desired, such as rate = 1/2, then higher order modulation schemes than QPSK would be required
- Conclusion: the 1bps/Hz requirement is onerous for radio manufacturers



Conclusion

- **To achieve high link deployment density**
  - ➢ **Advanced path coordination**
  - ➢ **ATPC especially for hub-and-spoke scenario**
- **Rules which enable initial development of low cost easy to install products**
  - ➢ **Smaller antennas with reduced EIRP**
  - ➢ **Reduced ATPC dynamic range for lower power devices**
  - ➢ **Eliminate or reduce channel loading requirement**
- **Growth path to higher power higher, higher data rate devices**
  - ➢ **Higher maximum EIRP with larger antennas**
  - ➢ **Higher order modulation**

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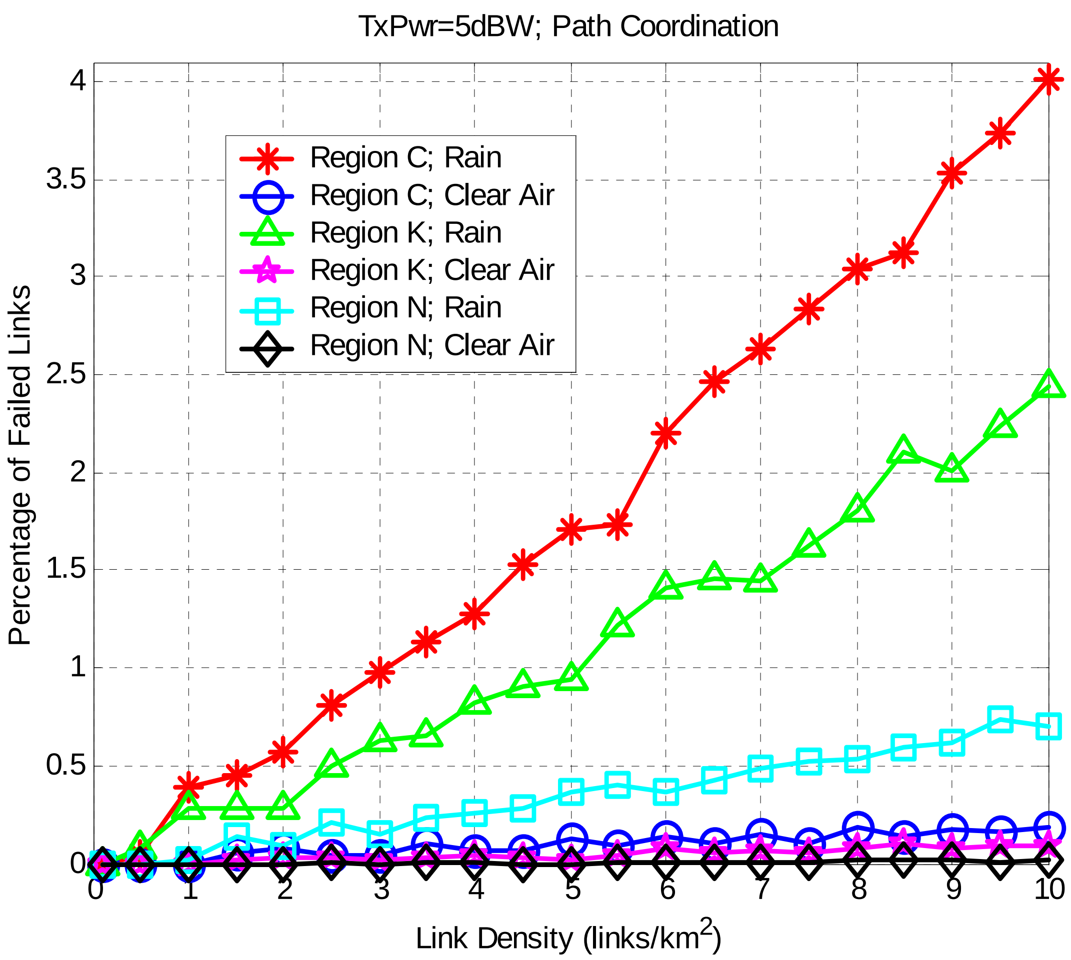
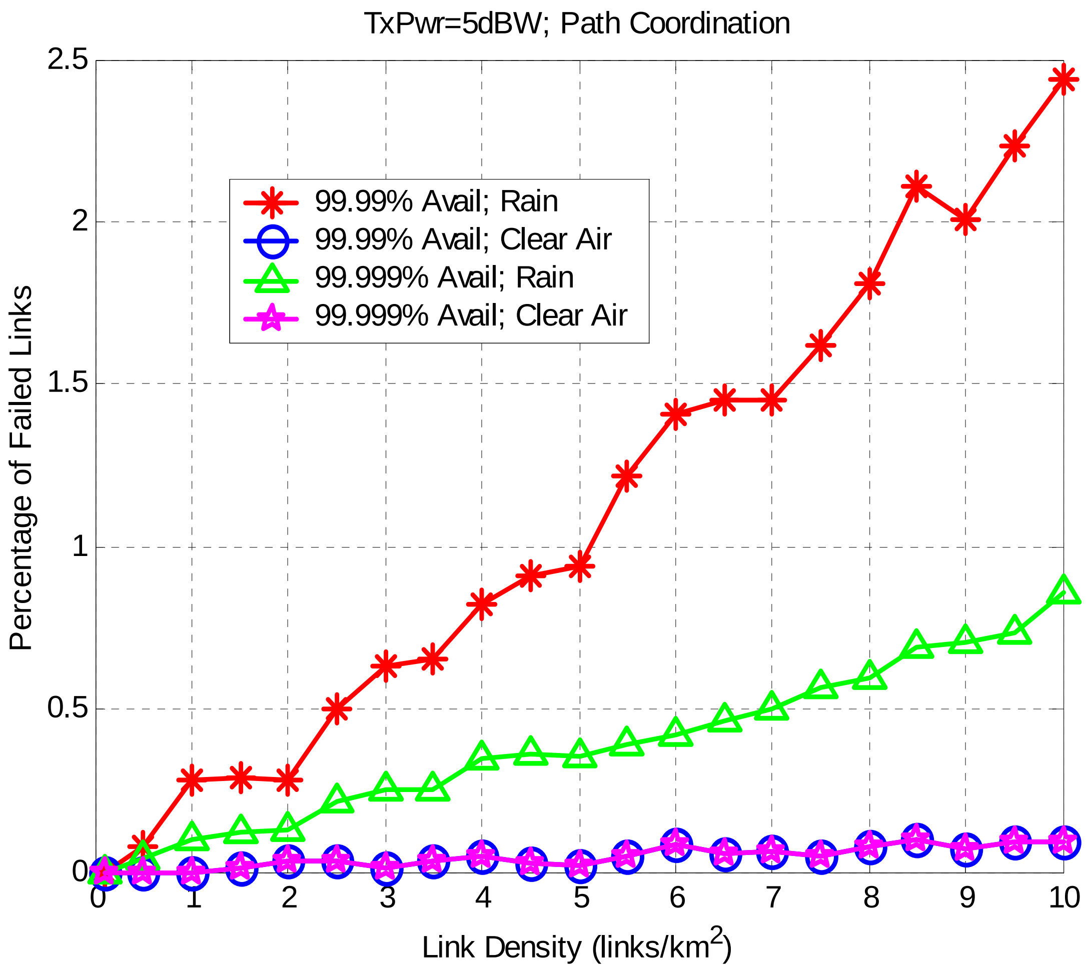
Other Simulation Results

Deployments in Different Rain Regions



- This slide shows the differences when the links are deployed for 99.99% availability in three different rain regions.
- Dry regions (Rain region C) lead to smaller fade margins and thus longer ranges. Longer ranges lead to lower C/I ratios for a given link density. The lower C/I ratios cause more links to have problems due to interference.
- Wet regions (Rain region N) lead to larger fade margins and thus shorter ranges, higher C/I ratios and fewer links that have problems due to interference.
- Rain region C suffers approximately 60% more link failures with interference than Rain region K; rain region N suffers approximately 1/3 fewer links with interference problems.

Deployments for Different Availabilities



- **The figure on this slide shows the differences when the links are deployed for 99.999% availability rather than 99.99% availability.**
- **Deployments for 99.999% availability need more link margin, so the links are significantly shorter. Shorter links lead to higher C/I ratios.**
- **Deployments for 99.999% availability encounter interference problems approximately 1/3 as often as deployments for 99.99% availability**

More Detail on Simulation Methodology

Detailed Flow of the Simulation

- **Calculate noise floor**
- **Select rain attenuation based on rain region and availability. Uniform rain assumed over entire area (we have separate simulations modeling moving rain cells).**
- **Determine maximum range based on link budget parameters**
- **Select a link density and determine the total number links based on 10 km x 10 km grid (i.e. 10links/km^2 => 1000 links)**
- **The following steps are repeated over 100 iterations**
  - **For each link, generate a random position for one end of the link**
  - **Generate a random path length for each link ranging from 100m to the maximum path length**
  - **Generate a random direction for each link (links must lie entirely in grid, otherwise a new direction is selected)**
  - **This defines the paths for all the links**
  - **Check to see if all links meet or exceed the required C/N (plus 1 dB on interference margin). If not, recompute paths for those links.**
    - **Perfect antenna pointing is assumed resulting in boresight antenna gain.**
  - **Generate a random frequency based on dual-band FDD (i.e. 70GHz east-west, 80GHz west-east or vice-versa) and random polarization for each link**

Detailed Flow of the Simulation, cont'd

- Reduce Tx power levels on each link based on ATPC
  - Transmit power is only reduced by a maximum amount as specified by the ATPC dynamic range rule
  - The transmit power is only reduced by an amount that maintains an ATPC margin of at least 10dB over the required C/N
- For each terminal, calculate interference from every other terminal in system
  - Line-of-sight assumed between all links
  - Angle off boresight for interferer transmission and angle off boresight for terminal of interest reception computed. Angles used to compute transmit and receive antenna gain and cross pol rejection
  - Rain attenuation and oxygen absorption calculated based on path length between interferer and terminal of interest
  - 80GHz transmission causes no interference to 70GHz receiver and vice-versa
  - Cross pol signal levels adjusted based on cross pol mask
- C/(N+I) is calculated for each link in both directions
- If a link has a C/(N+I) which is below the required C/N (in either direction) the link is considered to have failed.
- The percentage of failed links is calculated
- To model path coordination, the frequency direction and polarization is changed for the links that failed and the lowest percentage of failed links is saved

- The percentage of failed links is averaged over the 100 iterations
- All steps are repeated for the desired range of link densities

Complete List of Sensitivity Analysis

- Random deployment
- Hub-and-spoke deployment
- Antenna
  - Half power beamwidth
  - Front to back ratio
  - Cross pol
- Maximum EIRP
- Rain
  - Rain regions
  - Rain availability
  - Moving rain cells
  - (also clear air)
- ATPC
  - Transmitter power dynamic range
  - Adaptation based on
    - ✓ C/N
    - ✓ C/(N+I)
    - ✓ PFD
- Path coordination
- GPS coordinate accuracy
- Required SNR
- TDD/FDD
- Long, low availability link